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ADVANCES AND FUTURE NEEDS IN PARTICLE PRODUCTION AND TRANSPORT CODE DEVELOPMENTS*†

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Abstract

The next generation of accelerators and ever expanding needs of existing accelerators demand new developments and additions to Monte-Carlo codes, with an emphasis on enhanced modeling of elementary particle and heavy-ion interactions and transport. Challenges arise from extremely high beam energies and beam power, increasing complexity of accelerators and experimental setups, as well as design, engineering and performance constraints. All these put unprecedented requirements on the accuracy of particle production predictions, the capability and reliability of the codes used in planning new accelerator facilities and experiments, the design of machine, target and collimation systems, detectors and radiation shielding and minimization of their impact on environment. Recent advances in widely-used general-purpose all-particle codes are described for the most critical modules such as particle production event generators, elementary particle and heavy ion transport in an energy range which spans up to 17 decades, nuclide inventory and macroscopic impact on materials, and dealing with complex geometry of accelerator and detector structures. Future requirements for developing physics models and Monte-Carlo codes are discussed.

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Advances and Future Needs in Particle Production and Transport Code Developments

1. Introduction

The next generation of accelerators and ever expanding needs of existing accelerators demand new developments and additions to Monte-Carlo codes, with an emphasis on enhanced modeling of elementary particle and heavy-ion interactions and transport. Challenges arise from extremely high beam energies and beam power, increasing complexity of accelerators and experimental setups, as well as design, engineering and performance constraints. All these put unprecedented requirements on the accuracy of particle production predictions, the capability and reliability of the codes used in planning new accelerator facilities and experiments, the design of machine, target and collimation systems, detectors and radiation shielding and minimization of their impact on environment. This leads not only to new research activities involving new materials and technologies, but also corresponding code developments whose predictive power and reliability being absolutely crucial.

2. Application Demands

Particle transport simulation tools and the physics models and calculations required in developing relevant codes are all driven by application. The most demanding applications are the high-power accelerators (e.g., spallation neutron sources and neutrino factories), heavy-ion and ADS facilities, high-energy colliders and medical. Here are a few examples of applications and corresponding issues addressed in the simulations:

- **High-power accelerators** operationally are limited by beam losses, not by current limitations. Conventional radiation shielding can be bulky, costly and not easily implemented. Only with a very efficient beam collimation system can one reduce uncontrolled beam losses in the machine to an allowable level, protecting personnel and components against excessive irradiation, maintain operational reliability over the life of the machine, provide acceptable hands-on maintenance conditions, and reduce the impact of radiation on the environment, under both normal operation and accident conditions.
- **High-power targetry.** Principal issues include: production and collection of maximum numbers of particles of interest; suppression of background particles in the beamline; target and beam window operational survival and lifetime (compatibility, fatigue, stress limits, erosion, remote handling and radiation damage); protection of focusing systems including provision for superconducting coil quench stability; heat loads, radiation damage and activation of components; thick shielding and spent beam handling (prompt radiation and ground-water activation).

- **<u>High-energy colliders:</u>** These include hadron (Tevatron, LHC), heavy-ion (RHIC, LHC), e^+e^- (ILC, CLIC), and muon colliders. Principal issues address overall machine and interaction region design; accelerator and detector component protection against beam-induced radiation load (superconducting magnets) and damage (heating, material integrity and component lifetime); electronics soft errors; and detector backgrounds. All particle interactions and transport need to be accurately treated to predict machine and detector performance, radiation damage, residual radiation (hands-on maintenance), air, soil, and ground water activation, and prompt radiation on surface and in underground experimental halls.

3. Simulation Codes: Recent Advances

Only with a very reliable and accurate simulation code based on modern physics models and data can one computationally fulfill the needs of the applications described. Five general-purpose, all-particle codes are in this category: FLUKA [1], GEANT [2], MARS [3], MCNPX [4] and PHITS [5] and they are used extensively worldwide for accelerator and space applications. A substantial amount of effort (up to several hundreds of man-years) has been put into development of these codes over the last few decades. The user communities for the codes reach several thousands of people worldwide. Particle energies in these codes can be as high as hundreds of TeV and as low as a fraction of an eV, thus spanning up to 17 decades. Some of these codes are well suited for heavy-ion beams. All five codes can handle very complex geometry, have powerful user-friendly built-in GUI interfaces with magnetic field and tally viewers, and variance reduction capabilities. Tallies include volume and surface distributions (1D to 3D) of particle flux, energy, reaction rate, energy deposition, residual nuclide inventory, prompt and residual dose equivalent, displacement-per-atom (DPA) for radiation damage, event logs, intermediate source terms, etc.

Recent advances in these codes – instigated by accelerator developmental needs – include: reliable description of cross-sections and particle yields from a fraction of eV to many TeV for hadron, photon and heavy-ion projectiles (event generators); precise modeling of leading particle production and low-momentum transfer processes (elastic, diffractive and inelastic), crucial for beam-loss and collimation studies; reliable modeling of π^0-production (electro-magnetic showers), K^0-production (neutrino and kaon rare decay experiments), proton-antiproton annihilation, and stopped hadrons and muons; nuclide inventory, residual dose, DPA, hydrogen and helium production; precise modeling of multiple Coulomb scattering with projectile and target form-factors included; reliable and CPU-efficient modeling of hadron, lepton and heavy-ion electromagnetic processes with knock-on electron treatment and - at high energies – bremsstrahlung, direct pair production; hadron/muon photo- and electro-production; accurate particle transport in arbitrary geometry in presence of magnetic fields with objects ranging in size from microns to kilometers; variance reduction techniques; enhanced tagging of origin of a given signal/tally – geometry, process and phase-space – invaluable for source term and sensitivity analyses; user-friendly geometry description and visual editing; interfaces to MAD, ANSYS and hydrodynamics codes.

An example of a state-of-the-art particle production module in MARS15 [3] is a Quark-Gluon String Model event generator LAQGSM [6] combined with the Fermi break-up model, the coalescence model, and the generalized evaporation-fission model. The module is used for photon, hadron and heavy-ion projectiles with energies ~1 MeV/A to 1 TeV/A. This provides a powerful fully theoretically-consistent modeling of exclusive and inclusive distributions of secondary particles, spallation, fission, and fragmentation products needed for numerous applications. Another example is a new module in MARS15 which performs detailed treatment of competing decay and capture with X-ray emission for stopping muons. This allows analysis and aids in accurate detection of X-ray spectra in fissile materials – a promising technique for use at the ports of entry. All new developments in the codes are always a subject for thorough benchmarking [7].

In a very modern approach to accelerator complexes like Tevatron, LHC and J-PARC, a realistic model of the whole machine for multi-turn beam loss, energy deposition, activation and radiation shielding studies is built by reading in MAD lattices directly and creating a complete geometry and magnetic field model in the framework of such codes as FLUKA, MARS and GEANT. Such realistic modeling takes time and substantial effort, but experience confirms enormous benefits and insight. Two examples of this feature in MARS are shown in Fig.1. The entire 3-GeV J-PARC ring and LHC machine as well as collider detectors CMS and ATLAS are built into the model with all the magnetic elements, materials, magnetic fields and shielding, thus allowing for thorough optimization of the design and performance.

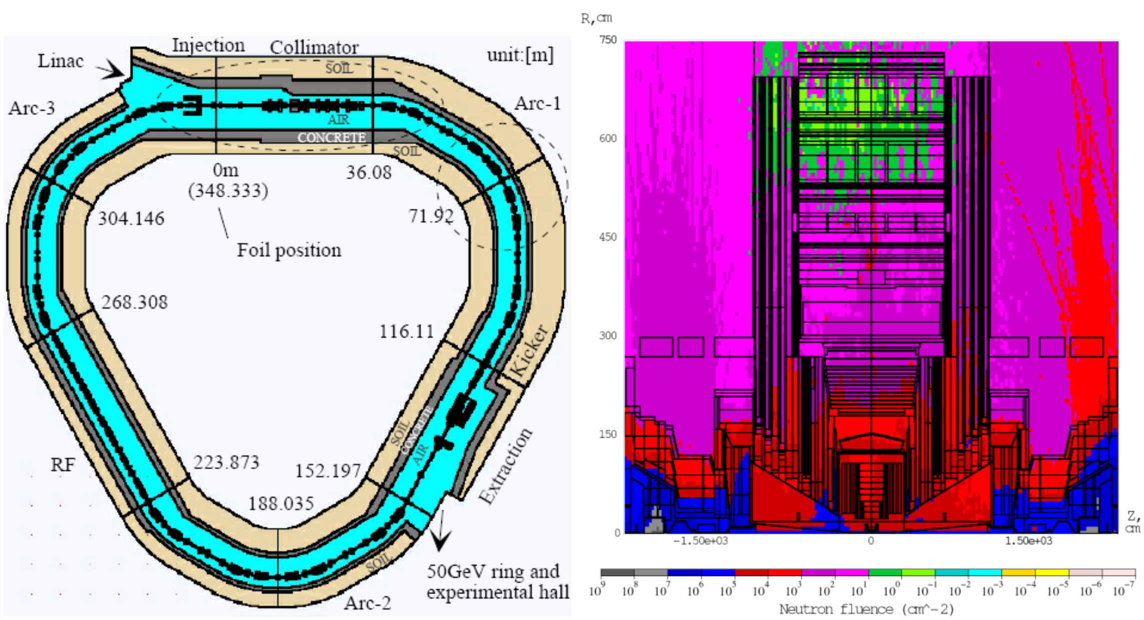

Fig. 1. MARS computer model of the entire J-PARC 3-GeV accelerator (left) and modeled neutron fluencies in the CMC detector at LHC for a kicker prefire accident with a 7-TeV proton beam (right).

4. Needs for Further Developments

The areas which require further development in Monte-Carlo codes and dedicated experiments to thoroughly benchmark include: further advancements in physics models for heavy ions including their physics and CPU performance; particle production event generators (low-energy pion and kaon yields, pre-equilibrium emission of heavy fragments, multi-fragmentation, photo-nuclear, muon and neutrino-induced reactions, and delayed particles); coupled energy deposition and hydrodynamics calculations; radiation effects (displacements per atom, single-event upsets, etc.); practical direct CAD links.

4. Conclusion

Presently there are several Monte-Carlo codes in the world which address the most challenging issues in R&D and design of radiation shielding, targets, collimators, detectors and, similarly, for high-power proton, electron, muon and heavy-ion beams. Impressive results and confirmation of models have been obtained over the last few years. The results of benchmarking on these widely-used codes are quite encouraging, and in some cases revealed underlying inconsistencies. Some problems/difficulties in the codes still exist and require further investigation and development.

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